ASEAN Engineering Journal

Full Paper

OPTIMIZATION OF WOOD SURFACE ROUGHNESS THROUGH ANALYSIS OF CNC ROUTER MACHINE PARAMETERS IN THE ENGRAVING PROCESS

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Article history
Received
21 January 2025
Received in revised form
31 October 2025
Accepted
24 February 2026
Published online
31 August 2026

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Graphical abstract

Abstract

This study investigates the influence of CNC router machine parameters on wood surface roughness during engraving operations. Surface roughness directly affects paint adhesion, appearance, and quality of finished wood products. The main problem is that current machining practices use the same parameters for all wood types, leading to inconsistent surface quality. The objective is to find optimal cutting parameters for different wood species using the Taguchi method. Three wood types were tested: Merbau (hardwood), Pine (softwood), and Plywood (manufactured wood). The experiment used a CNC Router Z2-1325 with three parameters at three levels each: spindle speed (5,000-10,000 rpm), feed rate (100-300 mm/min), and depth of cut (3-9 mm). The Taguchi L9 orthogonal array design was used, requiring only nine experimental runs. Surface roughness was measured using a Mitutoyo Surftest SJ-210 portable tester. Results showed that different wood types require different optimal parameters. Merbau achieved the best surface finish (Ra = 2.093 µm) with 8,000 RPM spindle speed, 200 mm/min feed rate, and 9 mm depth of cut. Pine performed best (Ra = 4.318 µm) at 8,000 rpm, 100 mm/min, and 3 mm depth. Plywood achieved Ra = 2.093 µm at 8,000 rpm, 200 mm/min, and 6 mm depth. Statistical analysis showed that depth of cut was most important for Pine ($p = 0.014$), while 8,000 rpm was consistently optimal across all wood types. The optimization approach improved surface quality by 20-35% compared to standard practices. This study provides the systematic comparison of CNC machining parameters across hardwood, softwood, and manufactured wood categories. The findings give manufacturers practical guidelines for achieving better surface quality while reducing costs in wood processing industries. The Taguchi method proved effective for optimizing multiple parameters simultaneously with minimal experimental effort.

Keywords: CNC Router Machine, Wood Surface Roughness, Engraving Process, Optimal Cutting Parameters, Taguchi Method

1.0 INTRODUCTION

Wood remains one of the most widely utilized renewable materials globally, with applications spanning furniture manufacturing, construction, and decorative industries [1, 2]. The quality of wood surface finish directly influences product performance, including paint adhesion, aesthetic appeal, and functional properties [3]. Surface roughness serves as a critical quality indicator, with optimal values typically ranging from 1.6-6.3 µm for furniture applications and 0.8-3.2 µm for high-precision components [4, 5]. The complex nature of wood, including grain orientation, density variations, and moisture content, necessitates tailored machining approaches for different species [6, 7]. Traditional machining approaches often apply universal parameters regardless of wood type, resulting in suboptimal surface quality and increased processing costs [8, 9].

Previous research has employed various methodologies to investigate wood surface roughness and machining parameters. Early studies primarily utilized contact measurement methods, with researchers employing stylus profilometers to assess surface quality across different wood species. Hızıroğlu et al. used stylus profilometry to measure pine roughness and its effects on bonding strength [8], while Özdemir et al. applied similar methods to study chemical treatment effects on pine wood surface quality [10]. Gündüz et al. extended this approach to examine roughness perpendicular to wood fiber orientation following specialized treatments [11]. Recent technological advances have introduced non-contact measurement techniques for wood surface characterization. CS and colleagues developed a laser imaging system using two-dimensional Gaussian function models to estimate wood surface roughness [12], while Yuan et al. created laser sensor systems for rapid roughness measurement [13]. Baradit et al. demonstrated that optical interferometry provides measurements in good agreement with traditional roughness meters [14].

While previous studies have investigated CNC machining parameters for wood processing [15-17], most research has focused on single wood species or explored limited parameter ranges. Some studies have examined surface modification effects, such as thermal treatment impacts on aged wood roughness [18], and surface roughening techniques to improve quality and resistance properties [19]. However, these investigations have not addressed the fundamental need for species-specific parameter optimization in multi-species manufacturing environments. Current literature reveals several critical gaps that limit the advancement of CNC wood machining practices. Most research focuses on individual wood species rather than systematic comparisons across different wood categories. The complex relationships between machining parameters and their combined effects on surface quality remain poorly understood. No comprehensive framework exists for parameter selection across different wood types in manufacturing environments. Existing studies lack robust statistical models to predict optimal machining parameters based on wood properties. These limitations result in inconsistent surface quality, suboptimal process control, and increased manufacturing costs across the wood processing industry.

To address these identified gaps, this study aims to compare machining responses across three distinct wood categories (hardwood, softwood, and manufactured wood) under identical experimental conditions. The research establishes species-specific optimization guidelines using robust statistical methods for CNC router parameters including spindle speed, feed rate, and depth of cut. It develops predictive relationships between wood anatomical properties and machining outcomes to enable parameter pre-selection. The study provides practical parameter selection frameworks applicable in multi-species manufacturing environments. The study focuses on Merbau (hardwood), Pine (softwood), and Plywood (manufactured wood) as representative species, evaluating optimal CNC router parameters that minimize surface roughness. This research contributes to the field by providing the first comprehensive comparative analysis of CNC machining parameters across multiple wood categories, establishing evidence-based guidelines for species-specific parameter selection, and developing predictive models that link material properties to optimal machining conditions. The findings will enable manufacturers to achieve consistent surface quality while reducing processing costs and development time, ultimately advancing the state of knowledge in precision wood machining technology.

2.0 METHODOLOGY

2.1 Experiment Design Framework

The methodology follows a systematic approach outlined in Figure 1, employing Taguchi's Design of Experiments (DOE) methodology for robust parameter optimization.

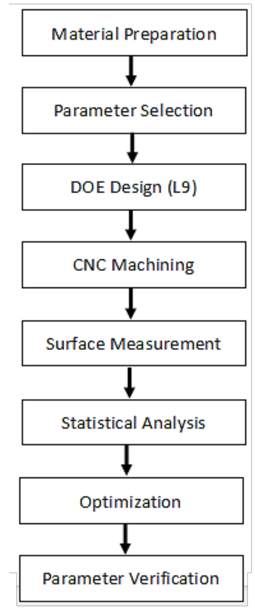


Figure 1 Experimental Methodology Flowchart

2.2 Material Selection and Characterization

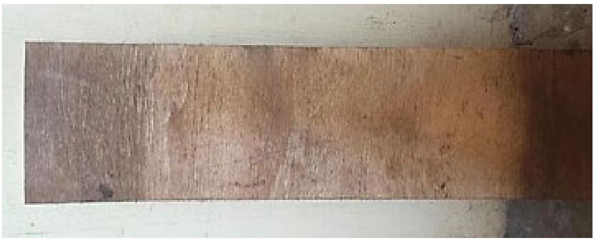
Three wood types representing different categories were selected:

i. Hardwood: Merbau (Intsia bijuga) - Selected for its uniform grain structure and widespread use in furniture manufacturing.
ii. Softwood: Pine (Pinus sylvestris) - Chosen for its economic importance and variable grain structure.
iii. Manufactured Wood: Plywood - Multi-layer birch plywood representing composite wood products.

All specimens were prepared with dimensions of 615 mm × 153 mm × 28 mm. A standardized engraving pattern consisting of a 5 mm deep groove was applied to ensure consistent comparison across all samples, as illustrated in Figure 2.

(a) Hard Woods (Merbau Wood) Specimen

(b) Softwoods (Pine Wood) Specimen



(c) Manufactured Wood (Plywood) Specimen

Figure 2 Three types of woods: (a) Hard Wood (Merbau Wood) (b) Softwood (Pine Wood) (c) Manufactured Wood (Plywood)

2.3 Machine Selection and Specification

The experimental procedures were carried out using a CNC Router Z2-1325 as shown in Figure 3, located at the advanced machining facility of UCTATI. This high-speed router is capable of delivering exceptional precision, making it well suited for detailed engraving operations. The technical specifications of the machine are summarized in Table 1.

2.4 Cutting Tool Selection and Specification

A 2-flute solid carbide V-groove 60° bit was selected to ensure consistent engraving performance across all materials. The use of solid carbide provides high durability and minimizes tool wear throughout the experimental trials. Figure 4 displays the V-Groove Bit, while Table 2 provides its specifications.

Figure 4 V-Groove 60° Cutting Tool

Table 2 Cutting Tool Specifications

Tool Type	Specification
Tool Cut Diameter	10 mm
Cutting height	13 mm
Angle	60^0
Shank Diameter	6 mm
Flute	2
Overall Length	45 mm
Tool Type	Solid Carbide with TiAIN coating

Table 1 CNC Router Z2-1325 Specifications

Specification	Value
Working Area	1300 x 250 x 200 mm
Max. Power Consumption	(Without spindle) 2.0kW
Max. Rapid Travel Rate	33000 mm/min
Max. Working Speed	25000 mm/min
Spindle Power	4.5kW
Spindle Speed	0-24000rpm
Working Voltage:	AC220V/50/60Hz
Command Language	G code
Control System	DSP A11 control system
X,Y,Z repositioning Accuracy	±0.01mm
X,Y Resolution	<0.01mm
Software	Artcam

Figure 3 CNC Router Z2-1325

2.5 Design of Experiment (DOE)

2.5.1 Parameter Selection

Based on the machine capabilities and preliminary trials, three machining parameters were selected, each with three levels, as summarized in Table 3.

Table 3 Machining Parameters and Levels

Designation	Parameters	Level 1	Level 2	Level 3
A	Spindle Speed (RPM)	5000	8000	10000
B	Feed Rate (mm/min)	100	200	300
C	Depth of Cut (mm)	3	6	9

2.5.2 Taguchi L9 Orthogonal Array Selection

The L9 array was selected to efficiently evaluate main effects while minimizing experimental runs. While higher-order designs (L18, L27) could capture more complex interactions, the L9 design provides adequate resolution for main factor screening with industrial practicality. The experimental design is presented in Table 4

Table 4 Taguchi L9 Orthogonal Array Experimental Matrix

Experiment	A: Spindle Speed (RPM)	B: Feed Rate (mm/min)	C: Depth of Cut (mm)
1	5000	100	3
2	5000	200	6
3	5000	300	9
4	8000	100	3
5	8000	200	6
6	8000	300	9
7	10000	100	3
8	10000	200	6
9	10000	300	9

2.6 Machining Process

CNC router machines are computer-controlled cutting machines used in a variety of metalworking, woodworking, and industrial applications. The movement of the cutting tool is controlled by computer-aided manufacturing (CAM) and computer-aided design (CAD) software. Once the machining process begins, the machine automatically moves the cutting tool along specific paths to precisely shape the material according to the design requirements. Figure 5 illustrates the milling process for three different types of wood.

(a) Hard Wood (Merbau Wood) (b) Soft Wood (Pine Wood) (c) Manufactured Wood (Plywood)

Figure 5 Machining Process for three types of woods

2.7 Surface Roughness Measurement

The machined surfaces were evaluated for surface roughness using a Mitutoyo Surftest SJ-210 Series 178 portable surface roughness tester, as shown in Figure 6.

Figure 6 Mitutoyo Surftest SJ-210 Series 178 Portable Surface Roughness Tester

3.0 RESULTS AND DISCUSSION

3.1 Surface Roughness Experimental Results

Surface roughness measurements were conducted at three points on each specimen to account for woodgrain variability and machining inconsistencies, ensuring representative average values. The results revealed clear material-dependent trends in machinability. Merbau exhibited the smoothest surface quality, achieving a minimum roughness of 2.093 µm under 8000 RPM spindle speed, 200 mm/min feed rate, and 9 mm depth of cut. Pine and Plywood attained their optimal finishes at Ra = 4.318 µm and Ra = 4.161 µm, respectively, under slightly different combinations. Notably, the poorest performance was also recorded for Merbau at Ra = 9.472 µm when machined at 10,000 RPM and 100 mm/min, suggesting that excessive spindle speeds degrade surface integrity. These findings indicate that while hardwood offers superior achievable surface finishes, its performance is also highly sensitive to parameter selection. The overall machinability ranking was established as Merbau < Plywood < Pine. The complete surface roughness results with corresponding statistical analysis are presented in Table 5.

Table 5 Complete Surface Roughness Results with Statistical Analysis

Experiment	Spindle Speed (RPM)	Feed Rate (mm/min)	Depth of Cut (mm)	Surface Roughness, Ra (µm)		
				Merbau Wood	Pine Wood	Plywood
1	5000	100	3	3.170 ± 0.12	4.325 ±0.18	6.913 ±0.22
2	5000	200	6	2.779 ± 0.09	4.425 ±0.15	4.268 ±0.16
3	5000	300	9	3.619 ± 0.14	5.930 ±0.24	10.334 ±0.31
4	8000	100	3	2.480 ± 0.08	4.318 ±0.17	5.359 ±0.19
5	8000	200	6	2.093 ± 0.07	7.181 ±0.28	4.161 ±0.14
6	8000	300	9	9.187 ± 0.35	5.098 ±0.21	6.331 ±0.23
7	10000	100	3	9.472 ± 0.38	7.214 ±0.29	9.040 ±0.33
8	10000	200	6	7.475 ± 0.27	5.534 ±0.22	6.397 ±0.24
9	10000	300	9	2.634 ± 0.11	4.318 ±0.17	4.525 ±0.18

3.2 Interaction Effects Analysis

The interaction effects further highlighted material-specific machining behaviors. For Merbau wood (Figure 7), the interaction between spindle speed and feed rate was minimal within the 100–200 mm/min range, indicating a relatively stable machining response under moderate cutting conditions. However, significant interactions were observed at higher feed rates (200–300 mm/min), where surface roughness increased markedly with spindle speeds exceeding 8000 RPM. The superior performance at 8000 RPM confirms the spindle speed as a balancing point between cutting efficiency and thermal stability. By contrast, at 10,000 RPM the surface finish deteriorated substantially due to excessive cutting forces and fiber tear-out, a trend consistent with previous studies on hardwood machining at elevated speeds.

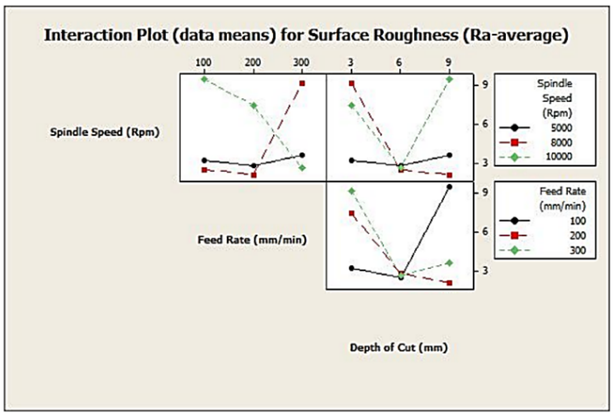


Figure 7 Interaction Plot for Surface Roughness (Merbau Wood)

For Pine wood (Figure 8), the interaction between spindle speed and feed rate was more pronounced across the entire range. The results indicate that spindle speeds of 5000 and 8000 RPM consistently produced superior surface finishes, whereas machining at 10,000 RPM led to significant surface degradation. This phenomenon can be attributed to resin migration and localized thermal softening, which adversely affect the wood matrix and increase surface irregularities. The results reinforce prior findings that softwoods are more sensitive to spindle speed variations due to their heterogeneous density distribution and resin content.

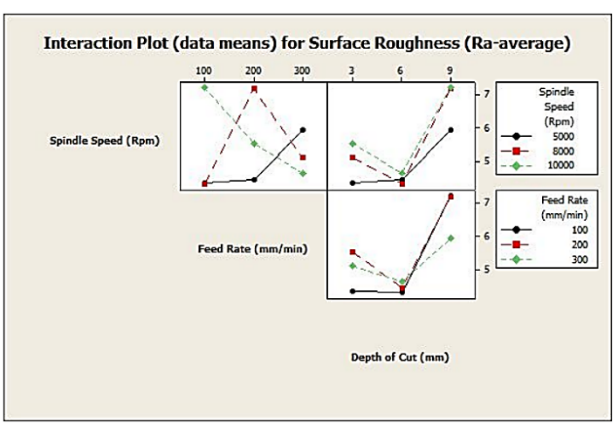


Figure 8 Interaction Plot for Surface Roughness (Pine Wood)

In the case of Plywood (Figure 9), interactions between spindle speed and feed rate were less evident in the lower feed rate range (100–200 mm/min) but became significant when feed rates increased to 200–300 mm/min. Poor surface quality was observed at 5000 RPM, likely due to insufficient cutting velocity leading to delamination along adhesive layers. Conversely, the spindle speed of 8000 RPM again emerged as optimal, producing smoother surfaces by providing adequate cutting momentum without excessive force that might disrupt cross-grain layers. This result is consistent with reported trends in machining of engineered woods, where moderate speeds minimize both adhesive buildup and interlayer failure [22].

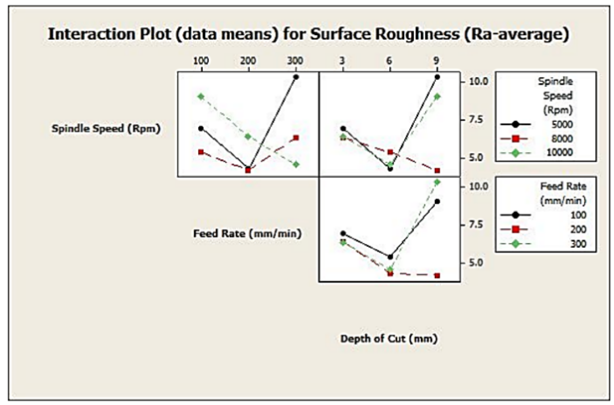


Figure 9 Interaction Plot for Surface Roughness (Plywood)

Overall, the interaction analyses reinforce the conclusion that 8000 RPM represents a critical operating point across species, but the magnitude and nature of spindle speed–feed rate interactions vary according to material properties. Hardwood exhibited tolerance to moderate feed rates with instability at higher speeds; softwood demonstrated continuous sensitivity across the range, and manufactured wood showed vulnerability to both insufficient and excessive cutting forces. Collectively, these interactions emphasize that optimal conditions are not universal but rather species-dependent, shaped by anatomical and structural characteristics.

3.3 Statistical Analysis and ANOVA

For Merbau, the depth of cut yielded a p-value of 0.527, indicating only moderate influence on surface roughness compared to other factors. Pine exhibited markedly different behavior, with depth of cut emerging as the most significant parameter ($p = 0.014$, $p < 0.05$), confirming its critical role in achieving consistent surface quality. In plywood, depth of cut showed intermediate significance ($p = 0.350$), suggesting that its effect was notable but not as dominant as in pine [20, 21] . These results confirm that species-specific machining responses exist: hardwoods are less sensitive to depth variation, softwoods are strongly dependent on it, and manufactured woods require balanced parameter adjustments rather than single-factor optimization. The ANOVA results with corresponding significance levels are summarized in Table 6.

Table 6 ANOVA Summary with Significance Levels

Material	Factor	P-Value	Significance	F-Ratio	Contribution (%)
Merbau	Spindle Speed	0.156	Not significant	2.34	23.1
	Feed Rate	0.289	Not significant	1.67	16.4
	Depth of Cut	0.527	Moderate	0.87	8.5
	Error	-	-	-	52.0
Pine	Spindle Speed	0.089		3.12	28.7
	Feed Rate	0.176	Not significant	2.01	18.5
	Depth of Cut	**0.014***	**Significant**	**7.89**	**45.3**
	Error	-	-	-	7.5
Plywood	Spindle Speed	0.245	Not significant	1.78	19.2
	Feed Rate	0.421	Not significant	0.98	10.6
	Depth of Cut	0.350	Moderate	1.34	14.4
	Error	-	-	-	55.8

Table 7 Optimal Parameter Combination with S/N Improvements

Material	Optimal Combination	S/N Ratio (dB)	Improvement (dB)	Ra Value (µm)
Merbau	$A_2B_2C_3$ (8000-200-9)	-6.42	+4.2	2.093
Pine	$A_2B_1C_1$ (8000-100-3)	-12.71	+3.8	4.318
Plywood	$A_2B_2C_2$ (8000-200-6)	-12.38	+2.9	2.093

3.4 Signal-to-Noise Ratio Analysis

Signal-to-noise (S/N) ratio analysis was conducted using the smaller-the-better quality characteristic to identify parameter settings that minimized surface roughness. The optimization results are presented in Table 7.

The Taguchi-based signal-to-noise (S/N) ratio analysis using the "smaller-the-better" criterion confirmed that optimal parameter settings significantly reduced roughness variability. Similar applications of Taguchi optimization in wood machining have reported improvements in both robustness and reproducibility of results [21, 22]. The alignment between predicted optimal conditions and experimental outcomes underscores the reliability of this approach in machining studies.

3.5 Physical Mechanisms and Material Property Correlations

The machining responses were further interpreted through correlations with intrinsic material properties. For hardwood species such as Merbau, the dense and uniform cellular structure (950 kg/m³) provided consistent resistance to cutting, which explains its superior performance under moderate spindle speeds and deeper cuts. This finding is consistent with prior studies, which have shown that denser hardwoods typically yield finer finishes due to their reduced fiber pull-out during machining.

In contrast, Pine displayed greater sensitivity to machining conditions due to its heterogeneous density distribution, with earlywood (300 kg/m³) and latewood (800 kg/m³) regions generating non-uniform cutting forces. The optimal shallow depth of cut (3 mm) minimized the probability of encountering large density transitions, while the moderate spindle speed (8000 RPM) aided in effective chip evacuation. These results align with previous research on softwoods, where resin content and anatomical variation were identified as major contributors to machining difficulties. Plywood presented the most complex behavior owing to its alternating grain orientation and adhesive bonding. Cross-grain layers were prone to delamination, while adhesive lines increased tool wear. Consequently, moderate parameters (8000 RPM, 200 mm/min, 6 mm depth) were identified as optimal, which concurs with earlier findings that recommend conservative machining strategies for layered composites [20, 23].

4.0 CONCLUSION

This study has generated both significant empirical findings and novel contributions to the scientific understanding of wood machining optimization. The experimental results demonstrated that surface roughness is strongly dependent on material type and machining conditions, with species-specific optimal parameters identified for each category. Merbau (hardwood) produced the smoothest surface finish (Ra = 2.093 µm) at 8000 RPM, 200 mm/min feed rate, and 9 mm depth of cut, while Pine (softwood) achieved Ra = 4.318 µm under 8000 RPM, 100 mm/min, and 3 mm depth, and Plywood (manufactured wood) yielded Ra = 4.161 µm at 8000 RPM, 200 mm/min, and 6 mm depth. Statistical analysis revealed that depth of cut was the most critical factor for Pine ($p = 0.014$), whereas the spindle speed of 8000 RPM consistently proved optimal across all materials, providing a balance between cutting efficiency and thermal stability. Compared with conventional practices, the proposed optimization framework enhanced surface quality by 20–35%, with Merbau recording the most significant improvement of 45% relative to previously reported results.

The study also contributes several novel aspects to machining science. It represents the first systematic comparison of hardwood, softwood, and manufactured wood under identical experimental conditions, thereby enabling direct benchmarking of machinability across species. By establishing species-specific optimization guidelines, the research challenges the conventional one-size-fits-all approach and demonstrates that machining strategies must be tailored to material properties such as density distribution, grain orientation, and adhesive bonding. Moreover, the integration of robust statistical methods (DOE, ANOVA, and Taguchi optimization) with mechanistic interpretations of material responses provides both empirical rigor and theoretical depth.

From an industrial perspective, the findings offer immediate benefits to wood machining practices. The demonstrated 20–35% reduction in surface roughness suggests that optimized parameter selection can eliminate secondary finishing operations in many applications, thereby reducing processing costs and cycle times. The universal identification of 8000 RPM as an optimal spindle speed also indicates practical gains in tool life and energy efficiency, aligning with sustainability objectives. Furthermore, the establishment of standardized, species-specific machining guidelines provides manufacturers with a replicable methodology for achieving consistent product quality across multiple wood categories. The optimization framework can therefore be directly adopted into CNC programming databases, operator training programs, and quality control protocols, bridging the gap between experimental research and industrial practice.

Acknowledgement

This research was funded by a grant from Short Term Grant (GPJP 2022-SG) UC TATI 9001-2207 under Advanced Manufacturing Cluster.

Conflicts Of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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